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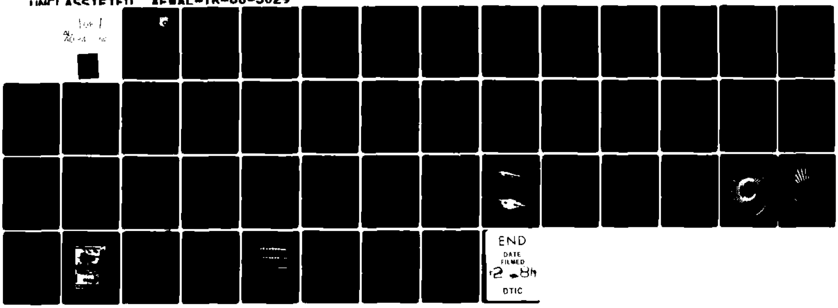

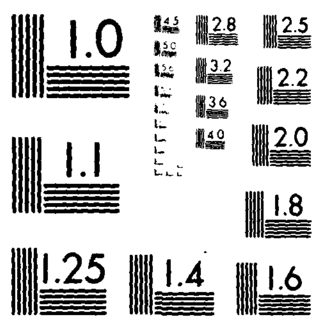

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EXPERIMENTS WITH A SUPERSONIC MULTI-CHANNEL RADIAL DIFFUSER

Siegfried H. Hasinger
Howard L. Toms Jr.
Thermomechanics Branch
Aero Mechanics Division

September 1980

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SIEGFRIED H. HASINGER
Aerosp Engr, Thermomechanics Branch
Aeromechanics Division

J. CHRISTOPHER BOISON
Chief, Thermomechanics Branch
Aeromechanics Division

FOR THE COMMANDER

PETER J. BUTKEWICZ, Col, USAF
Chief, Aeromechanics Division
Flight Dynamics Laboratory

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A supersonic radial flow diffuser of the type to be used for high energy radial flow lasers was investigated in cold flow experiments. The diffuser consisted of a multitude of small channels and it was the main purpose of the investigations to optimize the geometry of these channels. The nominal inlet Mach number of the diffuser was 3.5 and its axial length-to-diameter ratio referred to the inlet was 0.5. The maximum pressure recovery rate obtained with this diffuser was 80% of normal shock recovery. Selected channels tested

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individually reached a recovery rate of over 100%. Failure of the diffuser as a whole to reach this performance must be attributed to flow instabilities triggered by flow irregularities inherent to the present radial flow system.

FOREWORD

This is the final report on the investigations of supersonic radial diffusers, covering the experimental phase of this effort. This work was carried out under Work Unit No. 2307N435 of Project No. 2307 in the Thermomechanics Branch, Aeromechanics Division, Flight Dynamics Laboratory from November 1978 to September 1979. An earlier report on these investigations is AFWAL-TR-80-3028 entitled "Analysis and Design of a Supersonic Radial Outflow System".

Special recognition goes to Capt. David K. Miller who initiated this effort and followed it with great interest and valuable advice during the time he was in charge of this effort as Technical Manager.

A

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SECTION I

INTRODUCTION

The present investigations deal with an unusual type of diffuser, even as far as radial flow diffusers are concerned. There is no generally known supersonic radial diffuser. Even in the well known supersonic compressor, shock diffusion takes place in the rotor while the flow in the stationary diffuser is all subsonic. Its axial length-to-diameter (L/D) ratio distinguishes the present diffuser in particular from any other kind of radial flow diffuser. This ratio is many times larger than that commonly encountered with radial flow diffusers.

The need for this new type of diffuser stems from the development of airborne high energy lasers using a radial flow system. Such lasers require an axial L/D ratio referred to the diffuser inlet, of the order of three. Mach numbers of interest range from around three down to two. Nozzle throat Reynolds numbers typical for real laser systems are in the order of 10^4 and lower.

Since the aim in the present cold flow experiments was to explore the basic behavior of the radial flow diffuser, compliance with laser flow conditions in all details was not considered necessary. For a first approach, it was even desirable to minimize viscous effects and investigate them separately. To simplify experimental conditions, L/D was also minimized. Since a large Mach number accommodates the design of a radial flow expansion system (Reference 5) an upper limit was chosen for this number. Resulting nominal figures for the test rig were: $M = 3.5$, $\overset{*}{Re} = 5 \cdot 10^4$, and $L/D = 0.5$. For future explorations, the test rig had provisions to extend the L/D up to 3. The expansion nozzle system was designed for exchangeability with other nozzle systems. The complete test rig, which includes a three coordinate probe traversing mechanism, was designed for an eventual enclosure in a vacuum chamber for operation at lower pressure levels to reduce flow Reynolds numbers.

SECTION II

GENERAL ASPECTS FOR TESTING LARGE L/D RADIAL DIFFUSERS

1. HISTORY

Early experiments with this new type of diffuser were carried out by P. J. Ortwerth, et al (Reference 1). In this case, however, the L/D was only approximately 0.12. J. Howard and S. Hasinger reported in Reference 2 about a radial flow diffuser with an L/D increased to about 0.6. This diffuser was in axial as well as peripheral direction subdivided in a multitude of small channels ("egg-crate diffuser"). It was of a makeshift design and accomplished only 50% of normal shock recovery. It is the forerunner of the present diffuser, which is of the same type but fabricated more precisely and somewhat larger in absolute size. Its L/D is about 0.5, a value considered sufficiently large to determine the characteristic behavior of radial diffusers with a minimum of experimental complexities.

Professor J. Lee at Ohio State University has investigated a vaneless radial diffuser featuring contoured side walls to provide a near constant area flow passage for the diffusing flow (Reference 3). Without any subdivision of the flow, this type diffuser is restricted to comparatively small L/D values.

A radial flow diffuser subdivided only in peripheral direction by axially directed vanes has been investigated by United Technology Research Center, East Hartford, Connecticut;(Reference 4). The L/D of this diffuser is approximately 1.2. With this L/D value, the peripheral subdivision results in diffuser channels with a very high aspect ratio, i.e., the dimensions of the channel cross section are much larger in axial than in peripheral direction. This diffuser needs boundary layer energization at the diffuser endwalls for starting and maintaining a diffusing flow. The incentive for applying this type of vanes is the ease with which they can be fitted with cooling channels, a necessity for the actual laser application.

The present multi-channel diffuser is not readily adaptable to cooling. However, for the purpose of the present investigations it has the advantage of being quite adaptable to the fluid-dynamic needs for optimizing the diffuser performance. Results from the present investigations should be helpful for improving other diffuser types; in particular, the last one mentioned in respect to eliminating or reducing its need for boundary layer energization.

2. THE RADIAL FLOW FIELD

The present diffuser investigations are not only characterized by dealing with a unique flow field but also by fundamental difficulties in providing this flow field. This is due to the geometric constraints imposed on the flow source by the requirement for a large L/D. The restrictions are particularly severe for lower Mach numbers, say below 4, such as applicable here. Their severity depends also on operating conditions and the operating medium (Reference 5). The restrictions are more severe for the cold flow conditions used here than in the actual laser. The flow source developed here is therefore not necessarily typical for the actual laser system.

The need to utilize a multitude of expansion nozzles to produce the desired flow field is common to all large L/D radial flow systems. The exit flow of such systems inherently contains wakes produced by the individual nozzle walls. These wakes originate as boundary layers on the nozzle walls and are augmented by the sudden cross sectional area increase at the nozzle exits due to the finite thickness of the exit edges of the nozzles. Because of these flow disturbances, the expansion exit conditions can no longer be derived from simple potential flow considerations. Thus, the diffuser inlet flow given by the expansion in the ring nozzles and the subsequent expansion in the cavity between the nozzle system and the diffuser must either be determined experimentally or by analysis including all expansion losses. The present test arrangement does not allow an experimental determination since the expansion nozzles, because of the radial arrangement of the flow system, are not accessible to a flow survey with the diffuser in place and they

cannot be operated at design conditions with the diffuser removed. It was therefore necessary to determine the expansion nozzle performance analytically. This effort is reported in Reference 5. Its result, in the form of an effective diffuser inlet Mach number, is the basis for evaluating the test results with the present diffuser.

3. FLOW IRREGULARITIES

In addition to the flow disturbances given by the wakes of the nozzle walls, the geometric constraints of the radial expansion system are also responsible for flow irregularities which originate in the nozzle inlet region in connection with the nozzle support structure. These additional flow disturbances, which can have a very serious influence on the diffuser performance, cannot be completely eliminated and a considerable portion of the present effort was devoted to the attempt to minimize them.

SECTION III

DESCRIPTION OF THE FLOW SYSTEM

1. GENERAL DESCRIPTION

Figure 1 gives a schematic view of a cut through the complete radial flow system. It consists of a high pressure air supply tube, the expansion nozzle system consisting of a series of "ring nozzle," and the radial diffuser made up of a system of "diffuser plates." The space between the nozzle exits and the diffuser constitutes the "cavity" where the laser process takes place in the real system. Each of the end walls designated in Figure 1 with "top" and "bottom" according to their position in the test rig is provided with a row of port holes for measuring the static pressure distribution along one diffuser channel each on the top and bottom wall. The numbers assigned to the port holes are used for reference in the experiments. In the following, each element of the flow system is described in more details. For this description, reference is also made to Figure 2 which gives an assembly drawing of the radial flow system, including the support structure for the probe-traversing mechanism. The probe system itself is described at the end of this Section.

2. AIR SUPPLY TUBE

The supply tube supplies the incoming air uniformly along the axis of the flow system. It carries air of typically about 900 psig. Due to this high pressure, the inlet velocity of the air to the tube at both ends is very low ($M = 0.4$). The flow is throttled through the tube perforations to the pressure level prevailing ahead of the expansion nozzle system. Due to the limited space available between supply tube and nozzle inlet, the kinetic energy of the air expanding through the perforations cannot fully be dispersed. To obtain at least a random kinetic energy distribution, the flow is made to impact on the inside surface of the nozzle rings. Some dispersion of the flow is also obtained by the perforations being arranged inside the grooves, which should promote peripheral dispersion. Figure 3 gives a photograph of the supply tube.

3. RING NOZZLE SYSTEM

The radial flow admitted to the radial diffuser is generated in the expansion system which consists of a series of axially arranged rings as shown in Figure 4. Figure 5 is an engineering drawing of a nozzle ring together with a half ring needed at the ends of the nozzle system. The nozzle rings are kept centered and axially spaced by three spacer elements located 120° apart between the supply tube and the ring nozzles. One of the spacers is partially visible in Figure 4. Figure 6 is an engineering drawing for a spacer blank. For streamlining this blank it was shaped as outlined in the cross section A - A by hand filing. This spacer design permitted a very precise machining of the spacing dimensions and provided rigidity with a minimum of flow disturbance.

The nozzle ring spacers proved to be one of the most critical elements for the flow system design because of their influence on the diffuser performance. More details on the development of the present spacer are given in Section V.

The spacers function in the following way. The full size nozzle rings are held in place by the spacer grooves as indicated in Figure 6. The half rings are positioned at the ends of the spacers, as also shown in Figure 6. They are held in place together with the entire nozzle ring assembly by the two end pieces of the mounting system (Figure 2). The mounting forces are transmitted over the end pieces to the outside frame structure via springs and adjusting screws seen in Figure 2 as the smaller ones of two sets of springs and adjusting screws. The larger set holds the diffuser package together as described below. To prevent indentation of the nozzle rings or deformation of the spacers, they were made of 17-4PH stainless steel and hardened tool steel respectively. The following procedure was used to give the full size nozzle rings a tight seat. The dimension of the nozzle ring where it sits in the spacer groove was made slightly oversize (0.001"). At three locations 120° apart this oversize dimension was made slightly undersize (≈0.001"). The rings were mounted first with their undersize portions in the spacer grooves. For tightening, they were then rotated to engage the oversize portion of the ring seats

in the spacer grooves until they were sufficiently tight. To assure this engagement, a very small amount of Eastman 910-type glue was added at the contact points between the rings and the spacers. This system proved to be very reliable. The accuracy of the radial as well as the axial spacing of the nozzle rings is estimated to have been within ±0.002".

The expansion system also incorporated adjustable ring slots at both cavity side walls for injecting high pressure air to energize the wall boundary layers. These slots are formed by the back walls of the half nozzle rings and the end pieces holding the nozzle system in place. In Figure 2, the plenum chambers feeding the ring slots can be seen next to the half ring nozzles. In the present investigations, boundary layer injection was only used in an exploratory way and no results of particular consequence were obtained. None of the experiments reported here involves boundary layer injection.

A detailed flow analysis of the present ring nozzle system is given in Reference 5. It calculated an effective exit Mach number for the nozzle system of M = 3.102. For isentropic expansion in this nozzle system, a Mach number of M = 3.23 would be obtained. With the inclusion of the flow expansion in the cavity between nozzle exits and diffuser inlet considering also flow losses, the analysis of Reference 5 finds an effective Mach number of M = 3.514. This Mach number is the effective inlet Mach number of the radial diffuser.

4. RADIAL DIFFUSER

The radial diffuser is made up of a series of ring plates into which the individual diffuser channels have been cut by milling. The inner edges of these plates effect the axial subdivision of the flow while the pie shaped vanes (Figure 1) subdivide the flow in peripheral direction. Figure 7 presents an engineering drawing of the diffuser plates in their two forms necessary for assembling a complete diffuser package. To provide axial symmetry for the diffuser package, the plate in the middle of the package has channels milled on both sides as shown in Figure 7 as No. 2 plate. All other plates of the package are No. 1 plates. Two sets of

diffuser plates were fabricated, one with a constant area channel geometry and the other with a 0.9° taper as shown in Figure 7. Figure 8 shows an overall view and Figure 9 detail views of diffuser plates.

In subdividing any supersonic diffuser into small channels, the supersonic flow prevailing ahead of the throat should be exposed to a minimum of wall surface, i.e., the subdivision should be limited as much as possible to the diffuser portion downstream of the throat. This principle has been applied in Reference 6 to a straight flow, two-dimensional diffuser duct with a high aspect ratio. In this case it was shown that shock diffusion requires a near axisymmetric duct cross section to be completely effective.

The diffuser plates shown here provided basic channel shapes which could be changed by means of epoxy buildups. In this way, the inlet cross section contour and the diffuser throat dimensions were changed. These modifications are described in detail in Section V.

The diffuser package is mounted between the endwalls readily seen in Figure 2. Springs press the left end wall against the diffuser package. These springs had to be kept under very high tension to keep the diffuser plates from vibrating under the influence of the diffusing flow.

5. INSTRUMENTATION

a. Static Wall Pressure

To survey the flow in the test rig, the expansion plenum pressure, the cavity and diffuser wall pressures, and the exit pitot pressure of the diffuser could be measured. In addition, the flow rate and the pressure of the air supplied to the test rig could be recorded. Of these measurements, only the static wall pressures and the pitot exit pressure were essential for the test evaluation. Of these essential measurements, only the static pressure reading for the diffuser inlet (wall pressure tap #4 and #30) required a high degree of accuracy. The diffuser inlet pressure, together with the barometric pressure representing the diffuser exit pressure, determine the performance of the diffuser. Of the 288 individual diffuser

channels which make up the radial diffuser, the flow in only two channels, one on each end wall, could be surveyed by a row of 15 static pressure taps provided in the diffuser end walls (Figure 1). Both instrumented channels were at the same peripheral location and the ring nozzle system was always arranged in such a way that the ring nozzle spacers were positioned peripherally as much as possible away from the instrumented channels assuring a minimum disturbance of these channels by the spacers.

The accuracy with which the diffuser wall pressures could be determined was somewhat limited. These pressures were found as the difference of the barometric pressure and the suction pressure measured at the wall port hole. This suction pressure could be determined within an accuracy of approximately one third of one percent. Since the absolute wall pressure at the diffuser inlet was roughly one tenth of the measured suction pressure, the absolute wall pressure at the diffuser inlet could be obtained only with an accuracy of about 3%. Correspondingly, diffuser performance values given in terms of the percentage of normal shock pressure recovery can only be accurate to a similar degree. For the purpose of the present investigations, which was the determination of the general flow behavior of the radial diffuser, this accuracy was considered sufficient.

All other measurements were needed for qualitative observations only. The static wall pressure survey indicated the position of the shock system in the diffuser and the exit pitot pressure survey gave information about the peripheral uniformity of the flow, a factor which proved quite influential for the diffuser flow behavior.

b. Expansion Process

A flow survey of the expansion process was not possible as previously mentioned, but it was also not needed, since its performance could be determined analytically with sufficient accuracy. The measurements for the static pressure ahead of the nozzle system were very unreliable, since strong recirculating flows in the nozzle plenum area prevented exact static pressure measurements. Experience showed that such pressure measurements depended, for instance, on the arrangement of

the holes in the supply tube perforation. Reducing the hole size of the end rows of the perforation by about 30% in an earlier supply tube configuration which originally had uniform hole sizes (0.075 inches), reduced the static pressure reading for the nozzle plenum by about 10% however with no noticeable effect on the diffuser performance. The effect on the pressure reading may be explained in the following way. In the case of uniform size holes in the supply tube, the end nozzles receive an oversupply of air which leads to recirculation in the end portion of the nozzle plenum where the static pressure pick-ups are located (Figure 2). Since the flow coming from the supply tube is allowed to impinge on the inner nozzle ring wall, comparatively strong axial flow components may exist in the plenum; whereas radial flow components which affect the flow in the nozzles may be greatly attenuated. Because of the strong expansion of the flow in the nozzles, large flow irregularities can be tolerated upstream of the nozzles. The Mach number of the average radial flow component ahead of the nozzles is about 0.15. A 100% variation in this component can only cause a dynamic pressure variation in the expansion process which leads to an expansion Mach number variation of 1%, not taking into account any smoothing out of the flow during expansion. As further proof for the relative independence of the nozzle downstream conditions from the upstream flow irregularities is the negligible effect which the switch from a large hole to a small hole supply tube (Figure 3) had on the diffuser performance.

c. Traversing Mechanism

An important tool for the investigations proved to be the probe-traversing mechanism which allowed radial, axial, and peripheral movement of a probe for surveying the diffuser exit flow. Its main use was checking for the uniformity of the diffuser exit flow under the influence of non-uniformities in the inlet flow. An important alternate use of the traversing mechanism was the flow control of individual channels by means of a blocking body held in place and controlled by the traversing mechanism. A particularly useful function in this respect was moving the blocking body at a distinct setting from channel to channel around the periphery of the diffuser to check the performance limit of individual channels. (Section VI).

SECTION IV

RADIAL FLOW DIFFUSER TEST FACILITY

1. GENERAL SCHEME

A flow schematic of the facility for testing the Radial Flow Diffuser is shown in Figure 10. The entire flow chart may be grouped into three systems; the air supply, air regulation, and test apparatus. The air supply system consists of high pressure air (3000 psig) storage vessels, associated plumbing, and controls. The air regulation system consists of a two-stage pressure reduction regulating system, a two micron air filter, a mass flow venturi, assorted control valves, solenoid, pressure/temperature sensing elements, and three 80KW input electrical resistance heaters with associated controls and instrumentation. The test apparatus consists of the radial outflow system with diffuser assembly, a pressure probe traversing mechanism, associated pressure and temperature pick ups, and a calibration system.

All pressure measurements were recorded on a 12 channel strip chart recording system manufactured by S. Sterling Company. Each channel has individual balance, span, polarity reversal, and electrical calibration controls. The transducer signals are fed to three dual channel Texas Instrument Company Servo-Writer Mark II recorders mounted in the S. Sterling Company instrument cabinet. Six channels of information can be permanently recorded through a 12 channel switching matrix with an overall system accuracy of ±0.25% or ±5 micro-volts, whichever is greater.

The Radial Outflow Diffuser static wall pressures, both top and bottom, were sensed through a 48 channel Scanivalve pneumatic scanner, M/N SSS-48CBM/1248BCD/SLSN, using a 15 psid Statham differential pressure transducer, M/N PL131TC-15-350, whose output was recorded on the Texas Instrument Company Servo-Writer Mark II recorder.

Barometric pressure was measured on a Princo Instrument Inc., U.S. Signal Corps Tartan-type mercurial barometer before and after each test run as required.

Supply air temperature was measured with a 3/32" diameter Iron-constantan fast response thermocouple, manufactured by the Conax Company, and read out on a Sym-ply-trol pyrometer mounted on the operator's control panel.

Each data acquisition system was calibrated end-to-end before and after each test run. Pressure systems were calibrated against a laboratory precision Heise pressure gage or a 30 inch mercury manometer, depending on the absolute pressure levels encountered. Thermocouples were calibrated in an ice-water bath and in a laboratory single wall transite oven, manufactured by Blue M Electric Company, M/N SW-17-TA. The test points were 32°F and 400°F respectively, as indicated by a precision laboratory thermometer.

The typical supply air temperature for the test rig was 75°F.

2. MOUNTING OF THE FLOW SYSTEM

The radial flow system, together with the probe traversing mechanism, were mounted inside a special frame structure which can be seen in part in the photograph shown in Figure 11. The purpose of the frame structure was to take up all forces acting on the test rig in axial direction. The high pressure air supply tube was mounted floating in one of the end pieces of the flow system (Figure 2) and the air pressure forces in axial direction had to be taken up by the frame structure. The ring nozzle system and the diffuser package were held in place independently of each other by spring tension transmitted to the frame structure by springs and adjusting screws. This construction eliminated all danger of internal stresses due to temperature differences produced by Joule-Thompson cooling during the air expansion process.

The probe traversing mechanism could freely move inside the frame structure for surveying the diffuser package in peripheral, axial, and radial direction. Traversing speeds could be varied from about 2 to 10 inches per minute.

SECTION V

TEST PROCEDURE AND SYSTEM IMPROVEMENTS

1. DIFFUSER STARTING PROCESS

As with any supersonic diffuser, the radial flow diffuser must be started to reach its operational state. For the starting process, the pressure difference across the shock system which establishes itself in the cavity must be reduced. This allows the flow momentum forces to push the shock system downstream into the diffuser. In entering the diffuser, the shock system is able to provide better pressure recovery, increasing also the flow momentum forces which push the shock system further downstream toward the diffuser exit. Under this condition, a substantial portion of the diffuser walls is exposed to supersonic flow and thereby incurring flow losses. By increasing the pressure difference across the shock system, the flow pressure forces push the shock system again upstream toward the diffuser inlet with an increase in shock recovery ratio due to the reduction of wall flow losses. If the pressure difference is increased too much, the shock system is pushed out of the diffuser and the diffuser becomes unstarted. Since in the present experiments, the diffuser discharges to ambient, i.e. the diffuser exit pressure remains constant, the diffuser-starting process is controlled entirely by the upstream expansion pressure. Figure 12 gives a typical plot of the ring nozzle plenum pressure during start and unstart of the present diffuser.

The common picture of the diffuser starting process given above needs some amplification for the case of the radial flow diffuser. In the starting process, the shock system to be pushed into the diffuser has a very specific shape in the present case. Experimental evidence given in Reference 2 shows that the flow expanding in a ring nozzle system forms a well defined barrel-like shock front surrounding the nozzle system. The diameter of the barrel depends on the expansion pressure ratio. Increasing the pressure ratio makes the barrel grow. Reference 2 found a value of about 40% of normal shock recovery for the pressure recovery across this barrel shock front. As indicated in Reference 2, this shock front which has the appearance of a normal shock, is actually made up of a series of

oblique shocks formed between the wakes coming off the individual nozzle rings of the expansion system.

If the ring nozzle system is surrounded at some distance by a radial flow diffuser, the shock front, due to its barrel-like shape, reaches the center portion of the diffuser during the starting process before it reaches the portion near the end walls. Thus, the diffuser can only be started if the entire shock front reaches the diffuser.

For the operation of the multi-channel radial diffuser, a phenomenon observed during the investigations reported in Reference 2 is of particular significance here. When a piece of a small straight tube is immersed into the barrel shock, this tube by itself acts as a suction device since the supersonic flow entering the tube experiences a better pressure recovery inside the tube than across the barrel shock. Thus, diffusion can be improved locally in the flow system by placing diffuser channels into the flow where improvement is needed. Reference 2 reports some experiments with a wall diffuser. In this case, a single diffuser plate, the kind used here, (Figure 7) was placed on each end wall with the remaining portion of the radial flow passage left open. Due to the suction effect of these wall diffusers, the barrel shock remaining between the wall diffusers assumed a nearly cylindrical shape. Although the recovery rate was not improved, the result was a fairly uniform radial flow in the cavity.

In case of the present multi-channel diffuser, the channels in the middle of the diffuser package become started apparently before the end wall channels. The degree to which the started center channels support the starting of the end wall channels has so far not been determined. Present experimental experience has shown that starting the multi-channel diffuser, as far as pushing the shock system into the diffuser is concerned, generally occurs as a sudden event marked by a distinct reduction in flow noise. However, when the expansion supply pressure was raised very slowly, intermediate steps of starting could be distinguished. In contrast, unstart of the diffuser by lowering the supply pressure invariably occurred as a sudden conversion to fully unstarted conditions. In some rare cases, recovery from a beginning unstart to fully started condition

has been observed. For practical purposes, start and unstart of the diffuser were very distinct and reproducible events in terms of the required expansion pressure.

For the start and unstart behavior of a multi-channel diffuser, the weak channel effect must be taken into account. In starting the diffuser, a deficient performance of a single channel can be readily overcome by the good performance of the rest of the channels since, as we have seen from the single tube diffuser, channels can be started without being affected by their neighborhood flow conditions. The conditions are reversed for the unstart process where the shock systems are in all channels more or less positioned closely to the diffuser inlets. A single unstarted channel can precipitate an unstart process in its neighborhood and subsequently in the entire diffuser. Thus, the weakest channel should determine the overall diffuser performance (Section VI). A local disturbance in the source flow is equivalent to a weak channel. This was the prevalent case in the present flow system. As already pointed out, the system was inflicted with inherent non-uniformities, and a special effort had to be made as described in the next paragraph, to minimize these deficiencies.

2. PERFECTION OF THE FLOW SYSTEM

a. Flow Channel Alignment

An adjustment of the channel walls for the transition from the end nozzle rings (half rings) to the cavity wall was necessary. As described in Section III, the relative positions of these two elements were adjustable to form, if necessary, a boundary layer injection slot. For the present tests which do not employ boundary layer injection, this slot was closed in such a way that the back side of the half ring was made to line up with the cavity wall as close as possible. Because of the finite thickness of the half ring exit edge, there was a nominal step of 0.005" enlarging the flow path at this point. This adjustment was accomplished by shims placed underneath the support of the bottom end wall (Figure 2). It also necessitated a slight increase in the height of the diffuser plate package. This was done by gluing thin paper (≈0.002") on each plate. The alignment could be checked on the assembled system by a special gage inserted through the diffuser channels on the end walls.

b. Elimination of Peripheral Flow Irregularities

As mentioned before, the nozzle ring spacers were a principal cause for flow disturbances. In Figure 13, the pitot exit pressure of the diffuser was surveyed over the full circumference of one of the diffuser plates for three different types of spacers. These spacers are located 120° apart in the space between the high pressure air supply tube and the nozzle rings as described in Section III. Figure 14 gives a photograph of the three different types of spacers used in the survey. For the sheet-type spacer which was finally adopted for the diffuser experiments, an engineering drawing was already shown in Figure 6. The dimensional differences between the three types of spacers occur only in peripheral direction, i.e., their contours as viewed in peripheral direction do not change. Their radial extension was such that they did not reach into the ring nozzle throats (Figure 6).

The round type spacer used in the survey shown at the bottom of Figure 13 produced unexpectedly large disturbance. In this case, the flow in some of the channels located between the spacer positions is still supersonic. All surveys were made for the diffuser in started conditions. For the next spacer type with the sides flattened, the flow uniformity is improved; but the diffuser exit flow is still greatly disturbed, though no supersonic flows appear. For the sheet type spacer, the conditions are drastically improved as shown in the top survey. No influence of the spacers on the exit flow becomes apparent. For this spacer type, two axial surveys are also shown along the diffuser package. The flow fluctuations in this direction are somewhat larger than those found for the peripheral survey. Because of the generally good results with the sheet type spacer, no further attempts to improve the spacers were considered necessary.

3. TEST EVALUATION

To generalize the test results obtained in the form of diffuser wall pressure distributions, the measured pressures were related to the normal shock performance of the diffuser given by the diffuser inlet Mach number. The value of this Mach number is 3.514 as analytically determined

in Reference 5. The shock recovery ratio for this Mach number is 14.24 as given by common supersonic flow relations. The reference pressure for making measured pressures dimensionless is the diffuser exit pressure which would be obtained with normal shock recovery, i.e., the measured diffuser inlet pressure (pressure tap No. 3 or 31 in Figure 1) multiplied by 14.24 gives the reference pressure by which all measured values are to be divided. If the reference pressure is equal to the ambient pressure, which is always the diffuser exit pressure by design, pressure recovery is 100% of normal shock recovery.

4. DIFFUSER CHANNEL IMPROVEMENTS

The diffuser plates, as described in Section III, were designed with the intention of making small but critical flow cross section adjustments by means of epoxy layer buildups on the diffuser walls. With this in mind, the diffuser plates were fabricated with a moderate throat contraction of 0.86 (cross-sectional area ratio of throat to diffuser inlet) to assure starting of the diffuser in any case. The minimum theoretical contraction ratio is 0.69 for the Mach number prevailing here. Since the diffuser performance generally improves with increasing throat contraction up to the limit given by the diffuser starting conditions, wall adjustments of the fabricated plates were made to increase the contraction of the throat section. Another adjustment proved to be necessary for the diffuser plate inlet edges. In a radial flow system, a straight wedge profile produces a cross-sectional area reduction from inlet to throat which is similar to that of an inverted supersonic nozzle for parallel exit flow. This apparently ideal shape caused a delay in the onset of diffusion with otherwise no beneficial effects. A kind of ramp was built up by epoxy plastic on one side of the inlet edge to produce a near constant rate of area reduction in the diffuser inlet region ahead of the throat.

Figure 15 gives an account of all wall contour adjustments made to diffuser channels. In this figure, the flow cross-sectional area of the flow for one diffuser channel is plotted over the radius of the flow system for the various wall adjustments. The solid lines represent the conditions for the machined parts of the system. All other lines refer

to wall adjustments made by means of epoxy layer buildups. These adjustments were not always applied to the complete diffuser system. Instead, either the channels of one plate or only a few channels of one plate were fitted with these adjustments. One of the adjusted channels was always an instrumented one. As indicated in Section III the present test arrangement allowed throttling individual diffuser channels for checking whether a particular channel is capable of a higher pressure recovery than the radial diffuser as a whole was able to achieve. By throttling the instrumented channel, a quantitative performance comparison could be made for the various adjustments. The adjustment indicated in Figure 15 by the heavy dashed line was finally selected as particularly promising for applying to the complete diffuser, i.e., to all 288 channels of the system. The diffuser performance obtained with this optimized arrangement is described in Section VI. Experimental results about the influence of the channel geometry on the performance of a single channel in the radial diffuser are discussed in the following paragraphs.

The experiments showed that the diffuser performance is not particularly sensitive to the various channel adjustments. An example which presents typical upper and lower performance limits for the applied adjustments as found in single channel testing is shown in Figure 16. In this case, the diffuser package consisted of unmodified plates with constant area diffuser channels except for the top plate which was the same machined plate but had the throats adjusted for a contraction ratio of 0.75. A group of five channels on this plate, with the middle one instrumented, were modified to a throat contraction ratio of 0.62, which is below the minimum theoretical value (line 2 in Figure 15). In Figure 16, the performances of the two instrumented channels in this diffuser package, one channel unmodified with throat contraction 0.86, the other with contraction 0.62, are compared. The performances are plotted in terms of the percentage of normal shock recovery over the radius of cavity and diffuser (Section V). The unmodified channel with a throat contraction of 0.86 (constant area channel) reaches already 94% normal shock recovery, while with throat contraction of 0.62 the recovery ratio goes up to 107%. This is very close to the best single channel performance obtained in any of the present investigations

(Section VI). This good performance is of interest in connection with the prediction made in Reference 5, namely that a diffuser channel with a contraction followed by a short divergence changing into a constant area channel as applicable to line 2 of Figure 15 should yield favorable recovery ratios.

Figure 16 demonstrates the influence of the diffuser inlet edge adjustment described above. For the upper curve in Figure 16, one side of the inlet edge is recontoured as indicated in Figure 15 for curves 1 to 4. The lower curve in Figure 16 represents the pressure rise for the unmodified diffuser plate. For the adjusted inlet contour, the pressure rise begins earlier than in the case of the unadjusted diffuser plate. This earlier rise is advantageous since it reduces wall friction.

SECTION VI

SIGNIFICANT TEST RESULTS

1. GENERAL CONSIDERATIONS

At the beginning of the investigations, optimizing the diffuser channel geometry was considered the principal problem for perfecting the radial flow diffuser. However, during preliminary testing, it became apparent that deficiencies in the uniformity of the source flow had an overriding influence on the diffuser performance. The attempt to eliminate disturbances in the source flow as described in the previous Section to a degree that there would be no significant effect on the diffuser performance was not successful. The need for spacers to keep the ring nozzles in position makes the establishment of uniform peripheral flow conditions inherently difficult. A principal difficulty with diffusers is that the diffusing flow quite generally has a tendency to become unstable with increasing pressure recovery indicating that a diffuser has the tendency to amplify incoming flow disturbances rather than to smooth them out. Thus, flow stability rather than channel geometry appeared as the major problem in perfecting the present diffuser.

Single channel testing as described in the previous Section provided the means to separate effects on the diffuser performance caused by faulty channel geometry from those originating from a lack of flow stability.

2. TYPICAL RADIAL DIFFUSER PERFORMANCE

The diffuser pressure recovery curves shown in Figure 17 represent the outcome of an effort to bring the multi-channel diffuser to a reasonable degree of perfection in terms of providing a proper channel geometry and inlet flow uniformity. These curves must therefore be regarded as representing the typical performance of the present radial diffuser. The channel geometry in this case is that referred to in Figure 15 as adjustment (1). Two sets of curves have been plotted in Figure 17, representing two significant modes of operation at a condition where the diffuser operates at the lowest possible inlet pressure just short of becoming unstarted, i.e., the diffuser operates at the peak of its performance.

For the lower set of curves, all diffuser channels discharge to ambient. As can be seen from Figure 17, the diffuser as a whole achieves, as measured on both end walls of the cavity, a normal shock recovery rate of about 80%.

For the upper set of curves in Figure 17, the whole vertical row of six channels (see Figure 11 for the general arrangement of the channels) where the instrumented channels are located, was throttled by means of a blocking body attached to the probe traversing mechanism. Throttling of the exits of these channels was controlled by the radial movement of the blocking body by means of the traversing mechanism. In this throttling process, the channel exit pressure was raised without affecting the inlet pressure of the blocked channels, i.e., throttling simply moved the supersonic shock system in these channels upstream as close to the inlet as possible without causing unstart. To check the shock position, the static diffuser wall pressure near the diffuser inlet edge (pressure tap No. 5) was monitored to watch for changes of the pressure under the influence of the throttling process.

Figure 17 shows the selected channel row reached near 110% of normal shock recovery. This high recovery rate indicates that the channel geometry was sufficiently perfected. As mentioned before, the instrumented channels were always positioned away from the ring nozzle spacers to minimize flow disturbance from these spacers. Apparently, some kind of flow disturbance must have prevented the radial diffuser as a whole from reaching the same performance as the single channel.

Gross disturbances in the source flow were apparently not the cause for the performance difference as the peripheral pitot pressure survey of the diffuser exit, shown in Figure 13, indicated. This survey shows a fairly uniform pressure profile distribution with no evidence that any badly performing channel would spoil the overall performance of the diffuser. Comparatively small flow disturbances are apparently able to trigger the unstart of the diffuser.

In a search for weak channels which may cause premature unstart, a blockage survey was made. For this purpose, the blockage body which throttled the vertical row of channels at the location of the two instrumented channels was rotated with unchanged throttling position around the periphery of the diffuser package individually throttling each vertical row of the package. In this survey, two adjacent channel rows at a position close to one of the nozzle ring spacers, were found where blockage caused the entire diffuser to unstart, i. e., these two weak channel rows did not perform as well as the instrumented channels. To find other weak channels, the diffuser with no channel throttled was brought closer to unstart conditions by a particularly careful lowering of the system supply pressure. A blockage survey detected additional channel rows similar to the one found in the first survey. When the blockage survey was made with throttling somewhat reduced, i.e., with the blockage body slightly moved out, no unstart of the diffuser occurred around the entire circumference. This indicated that all channels tolerated some degree of throttling, i.e., singly or in small groups the diffuser channels are apparently able to perform better than the diffuser as a whole.

To shed more light on the flow stability in a radial diffuser, artificial disturbances were introduced and the mutual influence between channels was also studied as shown next.

3. FLOW STABILITY EXPERIMENTS

a. Spoiler Tests

To obtain some information about the magnitude of the flow disturbance which causes diffuser unstart in a blockage survey, a spoiler consisting of a simple wire (0.04" diameter) was hooked to the diffuser inlet plate edge in a channel located close to the channel originally found to be weak. A blockage survey resulted in diffusor unstart at the naturally weak channel and the spoiled channel. The spoiler was then placed in a channel on the opposite side of the diffuser. No unstart occurred in the spoiled channel during the blockage survey with the same throttling rate. It appeared that the diffuser had a weak side rather than an individually weak channel.

b. Mutual Interference Between Channels

To check how much interference takes place between channels just before unstart occurs, the diffuser wall pressure close to the inlet of the instrumented channel (pressure tap No. 7) was monitored during a blockage survey. Only if the diffuser was adjusted very closely to unstart condition did the monitored pressure change during the blockage survey. No change occurred for the monitored pressure during a blockage survey when the diffuser was adjusted with a safe margin before unstart occurred. In terms of expansion nozzle supply pressure, a safe margin typically meant 137 psig instead of 135 psig where unstart occurred.

The existence of some degree of mutual interference between the diffuser channels makes it plausible that the performance of the weakest channel determined by individual throttling is not necessarily identical to the overall performance of the diffuser. If the diffuser operates with a very safe unstart margin, no neighboring channels support the individually throttled channel to become unstarted, i. e., it shows a better performance than the diffuser as a whole where all channels are closer to unstart at the moment of diffuser unstart.

The inherent tendency of diffusing flows to become unstable with increasing pressure recovery provides the basic explanation for the performance discrepancies observed. The performance limit for the single channel supersonic diffuser is clearly given by the flow breakdown in the form of the diffuser unstart. However, before any single channel of the whole radial diffuser unstarts, the flow as a whole entering the radial diffuser is subject to possible instabilities. A local energy deficiency introduced in the radial outflow system is cause for a local pressure rise at the radial diffuser inlet locally decreasing the expansion energy produced in the nozzle system. This in turn decreases the local diffuser performance beyond the amount caused by the original disturbance. This is a flow condition which makes a local flow deficiency grow instead of suppressing it. Only the interaction with the surrounding flow determines whether a new flow equilibrium will be reached or at first a local flow breakdown, i.e., unstart of a single channel, and subsequently the unstart of the radial diffuser as a whole occurs.

SECTION VII

CONCLUSION

The present experiments have shown that a radial flow diffuser applying the multi-channel (egg-crate) concept can achieve about 80% of normal shock pressure recovery without the need for boundary layer energization. The failure to achieve full normal shock recovery must be traced to certain adverse flow conditions inherent to the system rather than to an inadequate diffuser channel geometry. As found for the two instrumented channels of the diffuser system, the pressure recovery in single channels could be readily raised to levels of normal shock recovery by individually throttling their exits without otherwise affecting the diffuser. Excessive throttling caused unstart of the whole diffuser. By surveying all channels for the individual amount of throttling necessary to unstart the diffuser as a whole, it was found that inferior channels existed which tolerated less throttling than other channels. Since, however, all channels tolerated some throttling before the diffuser as a whole became unstarted, it appeared that the single channel performance was always better than the performance of the diffuser as a whole. Another essential finding of the investigations was that a peripheral pitot pressure survey of the radial diffuser exit did not reveal any clear evidence for inferior channels, instead the exit flow profiles for individual channels were fairly uniform. In view of the general fact that diffusing flows have a natural tendency to become unstable, the absence of obvious flow deficiencies in the system leads to the conclusion that instabilities in the diffuser inlet flow sensitive to small flow changes are the basic cause for the considerable differences observed between the performances of single channels and the diffuser as a whole.

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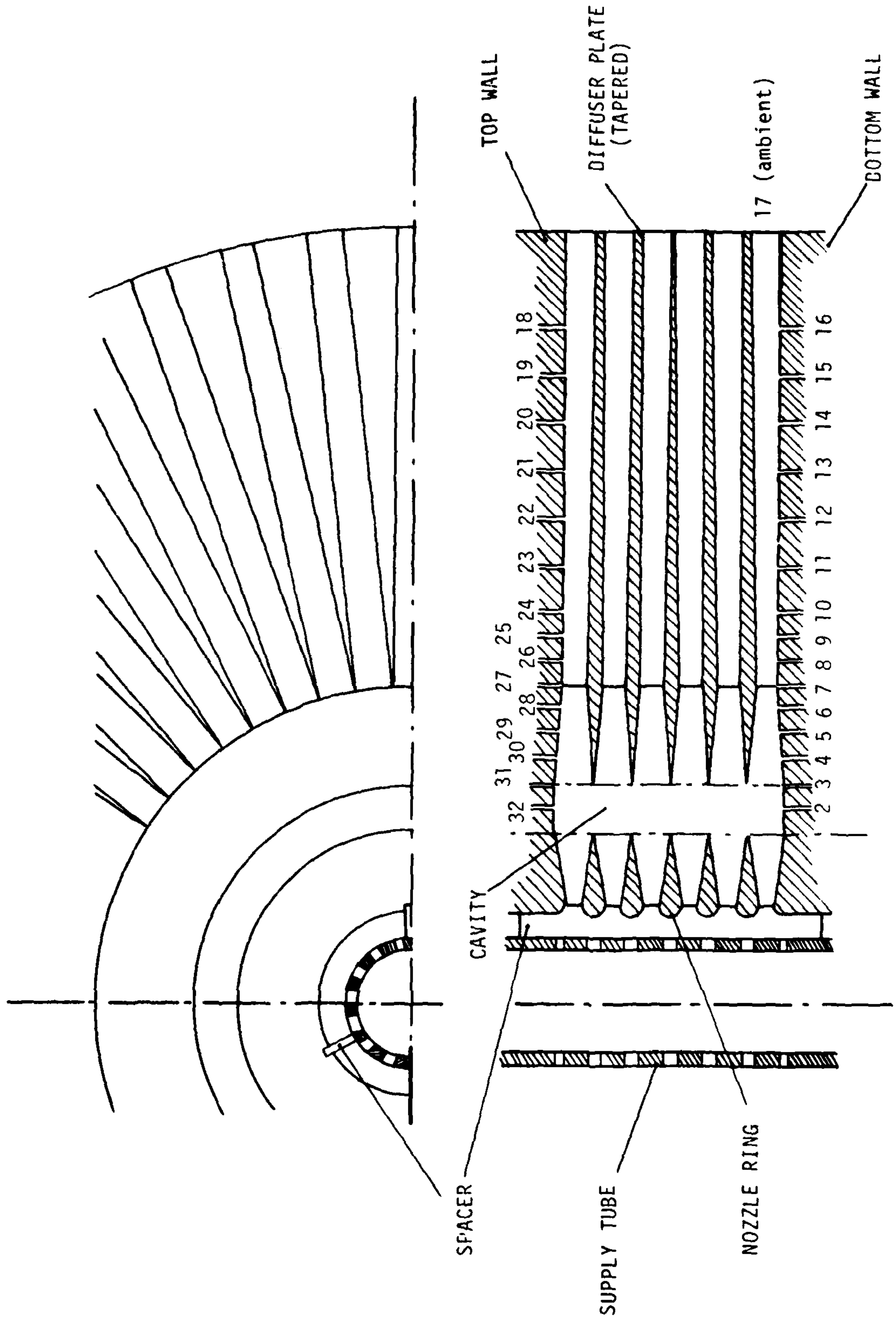

Figure 1. Scheme of the Radial Flow System

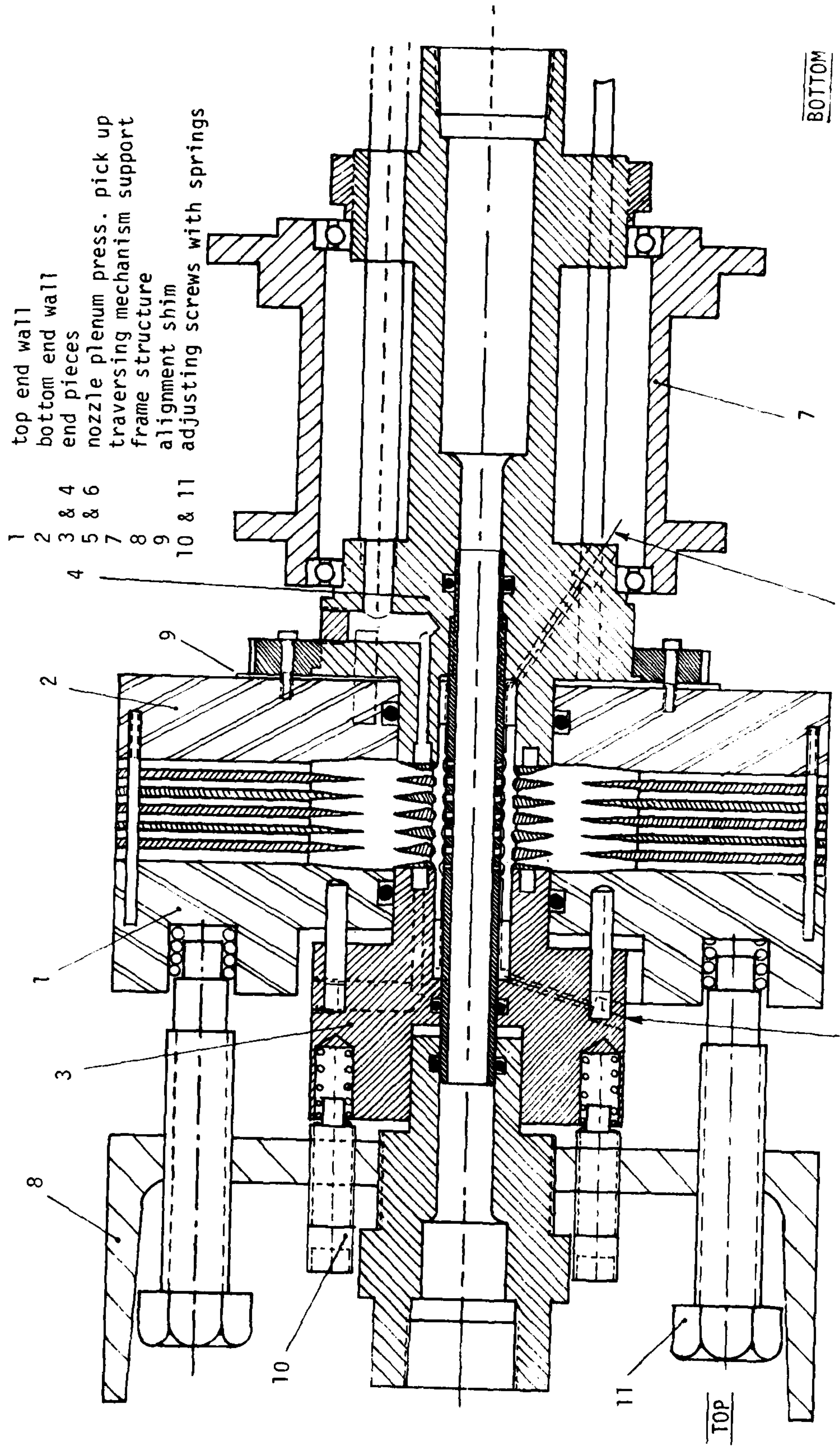

Figure 2. Test Rig Assembly Drawing

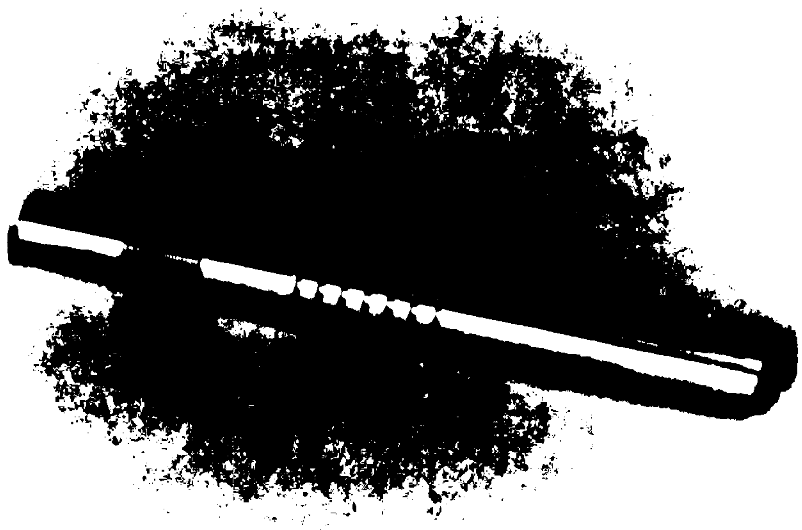

Figure 3. High Pressure Air Supply Tube

Length: [illegible], diameter: [illegible]

perforations: 0.052" diam except end rows (0.03[illegible])

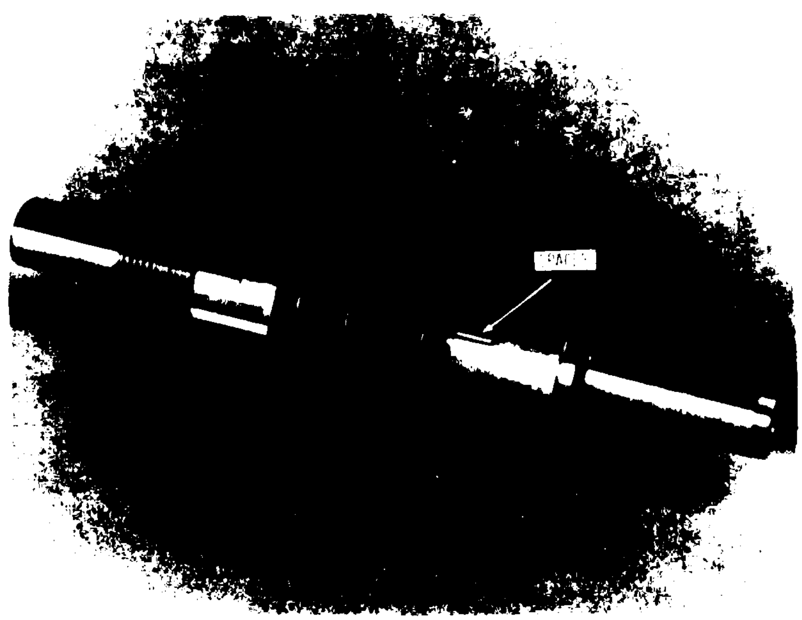

Figure 4. Ring Nozzle System

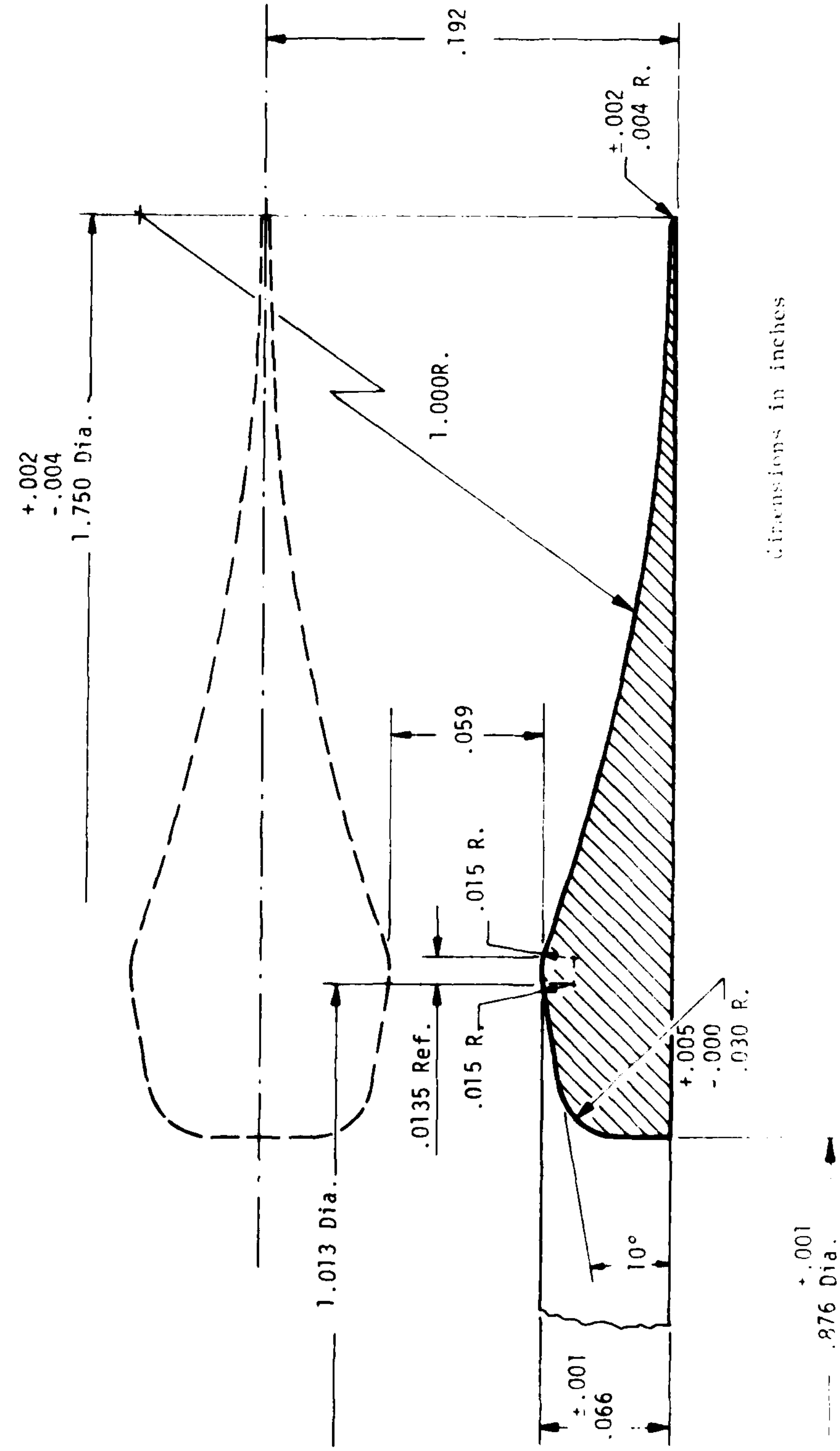

Figure 5. Nozzle Ring Drawing (Full Ring and Half Ring)

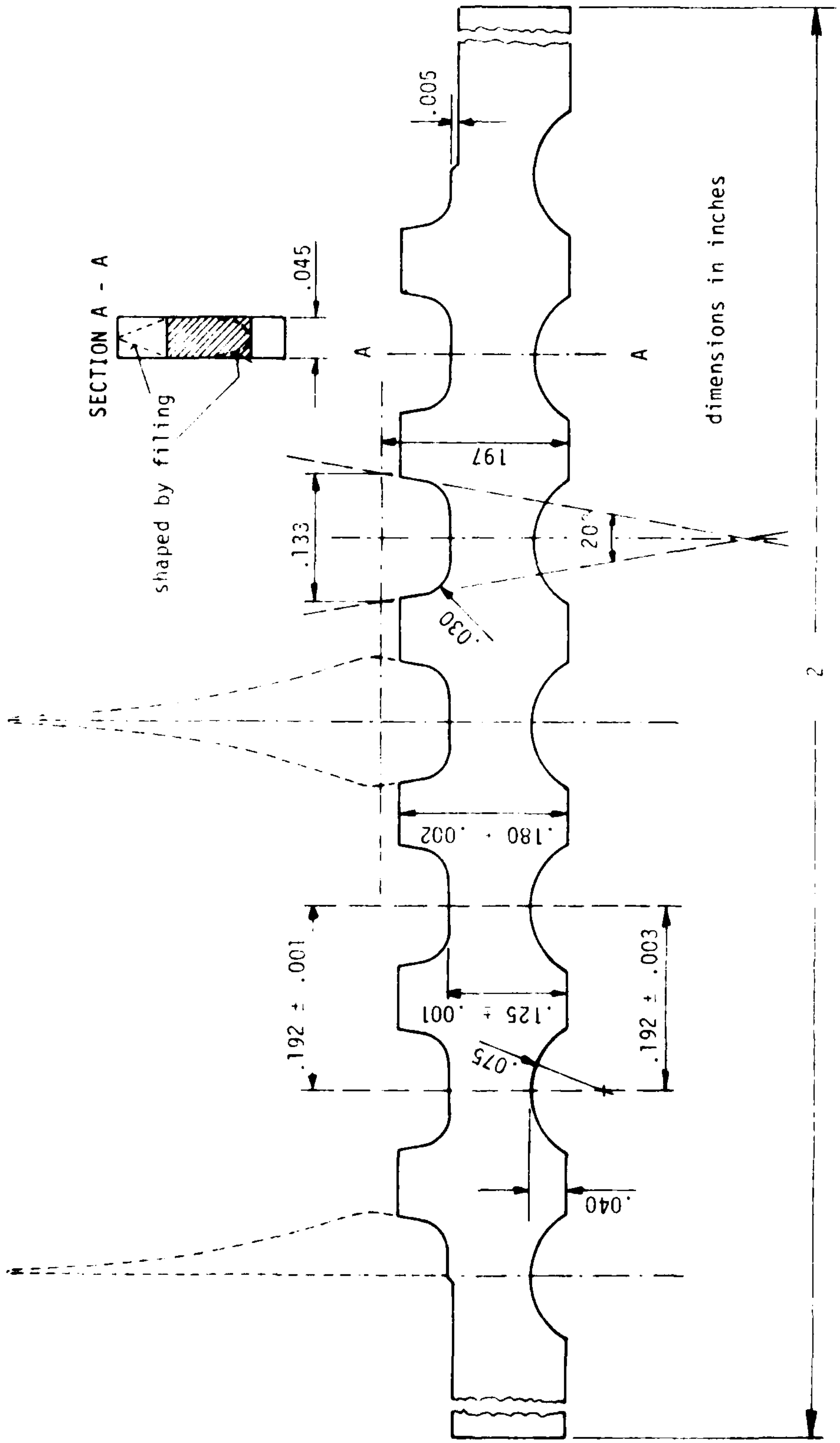

Figure 6. Nozzle Ring Spacer Drawing (Final Version)

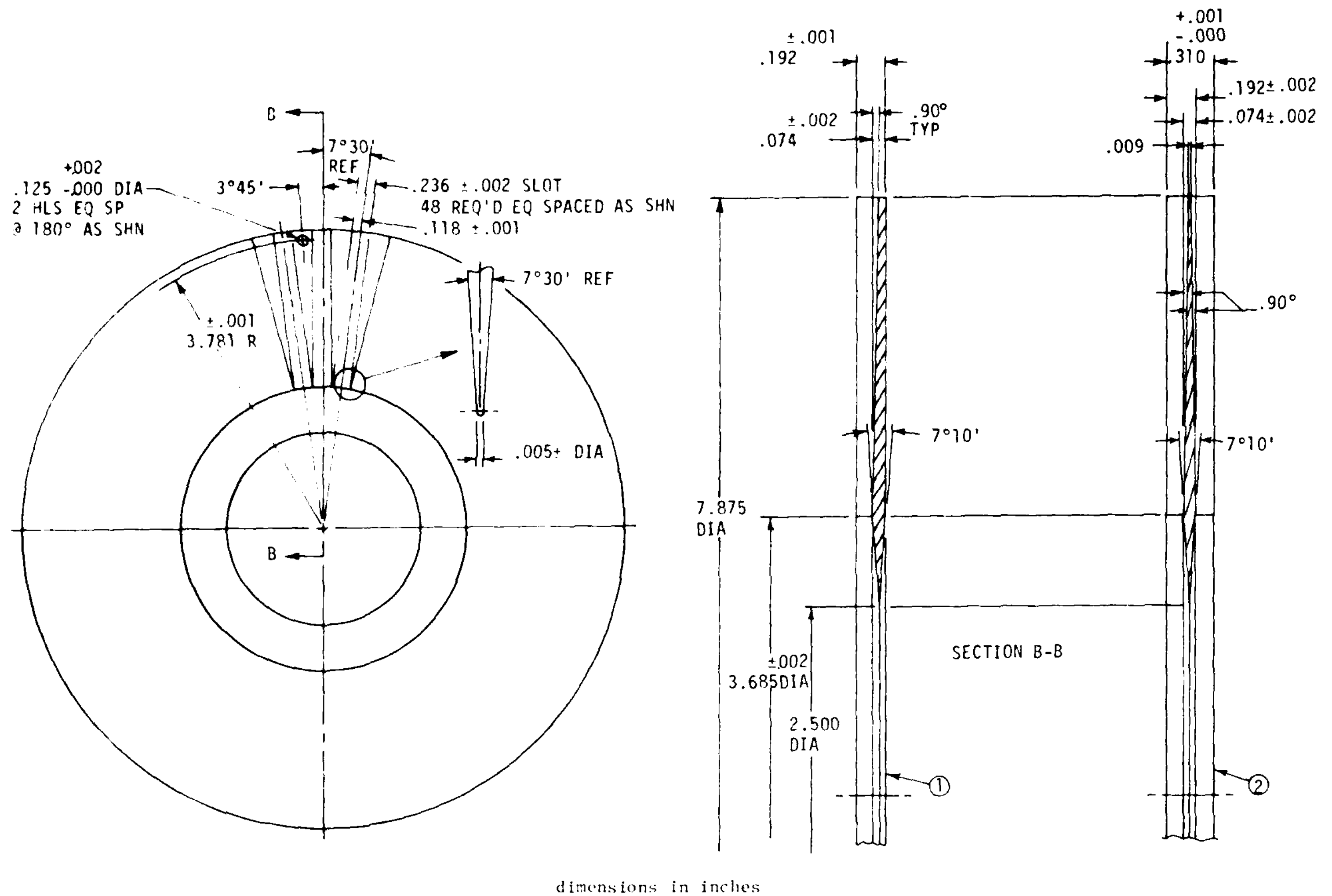

Figure 7. Engineering Drawing for Diffuser Plate (Tapered Channels)

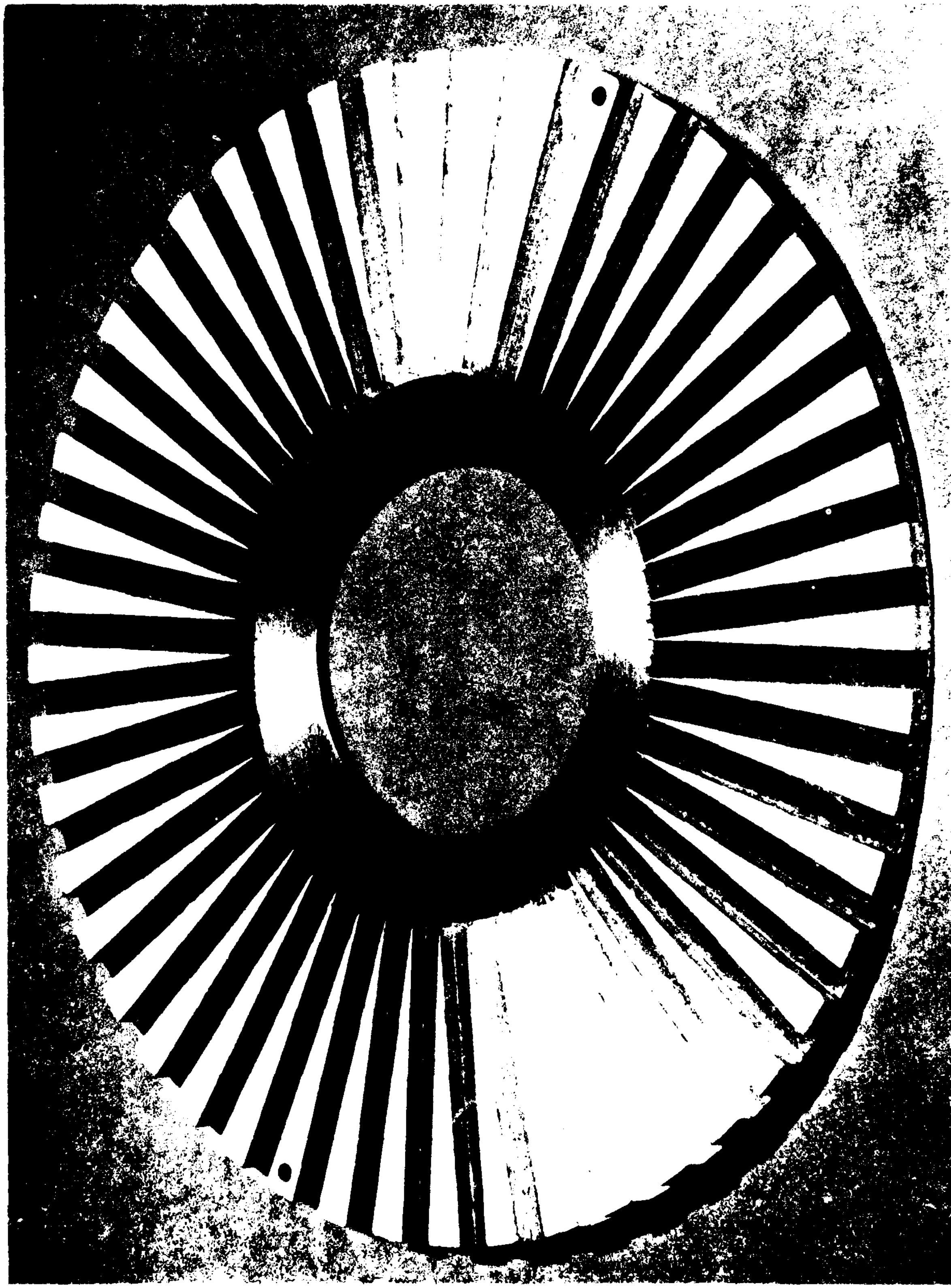

Figure 8. Photographic View of Diffuser Plate (Tapered Channels)

Figure 9a. Close-up View of Diffuser Plate (Tapered [illegible])

Figure 9b. Close-up View of Diffuser Plate with Wall Adjacent

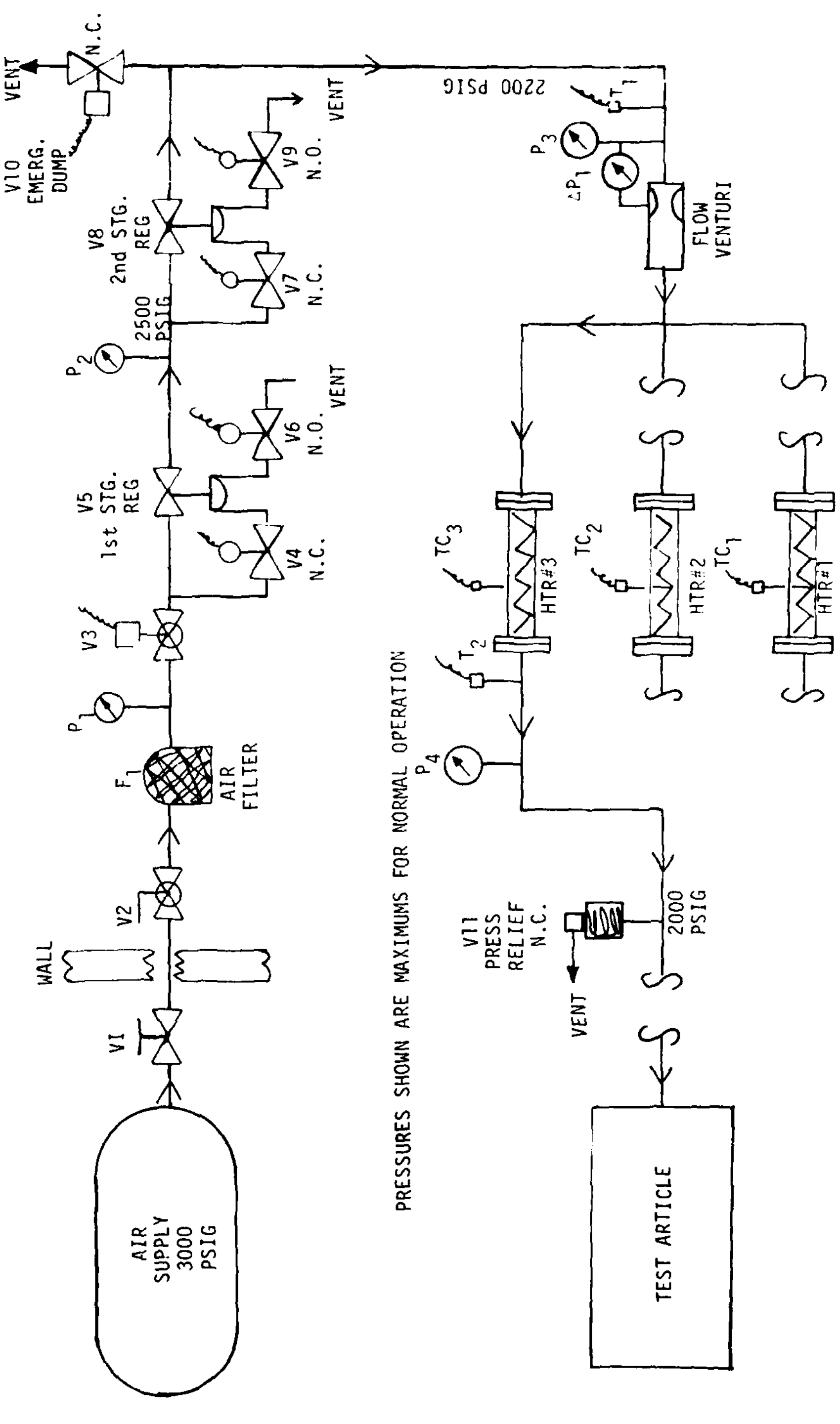

Figure 10. Schematic of Test Facility Used for the Radial Diffuser Investigations

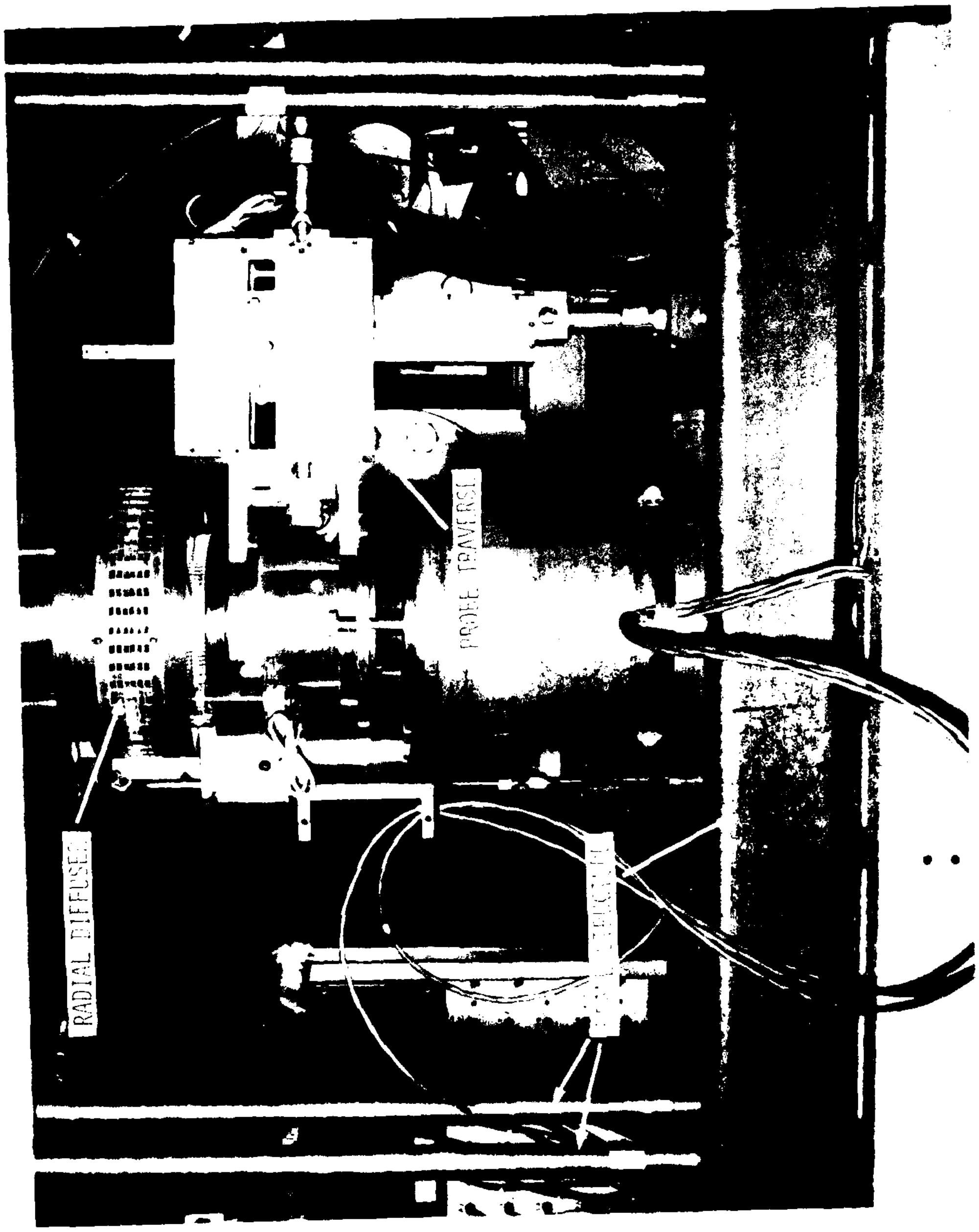

Figure 11. View of Radial Diffuser Test Rig (Radial Flow System Mounted Inside Frame Structure)

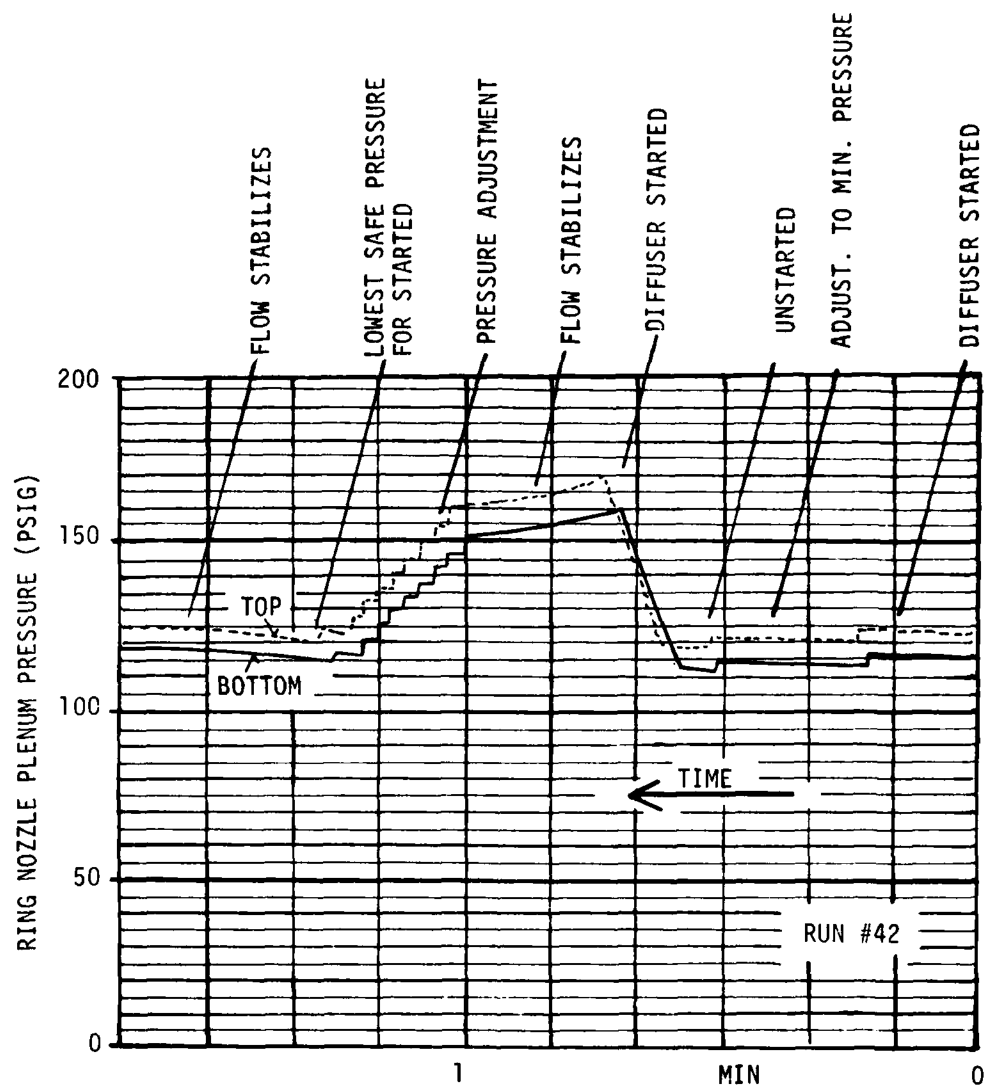

Figure 12. Typical Change of Expansion Plenum Pressure During "Start" and "Unstart" of the Radial Flow Diffuser

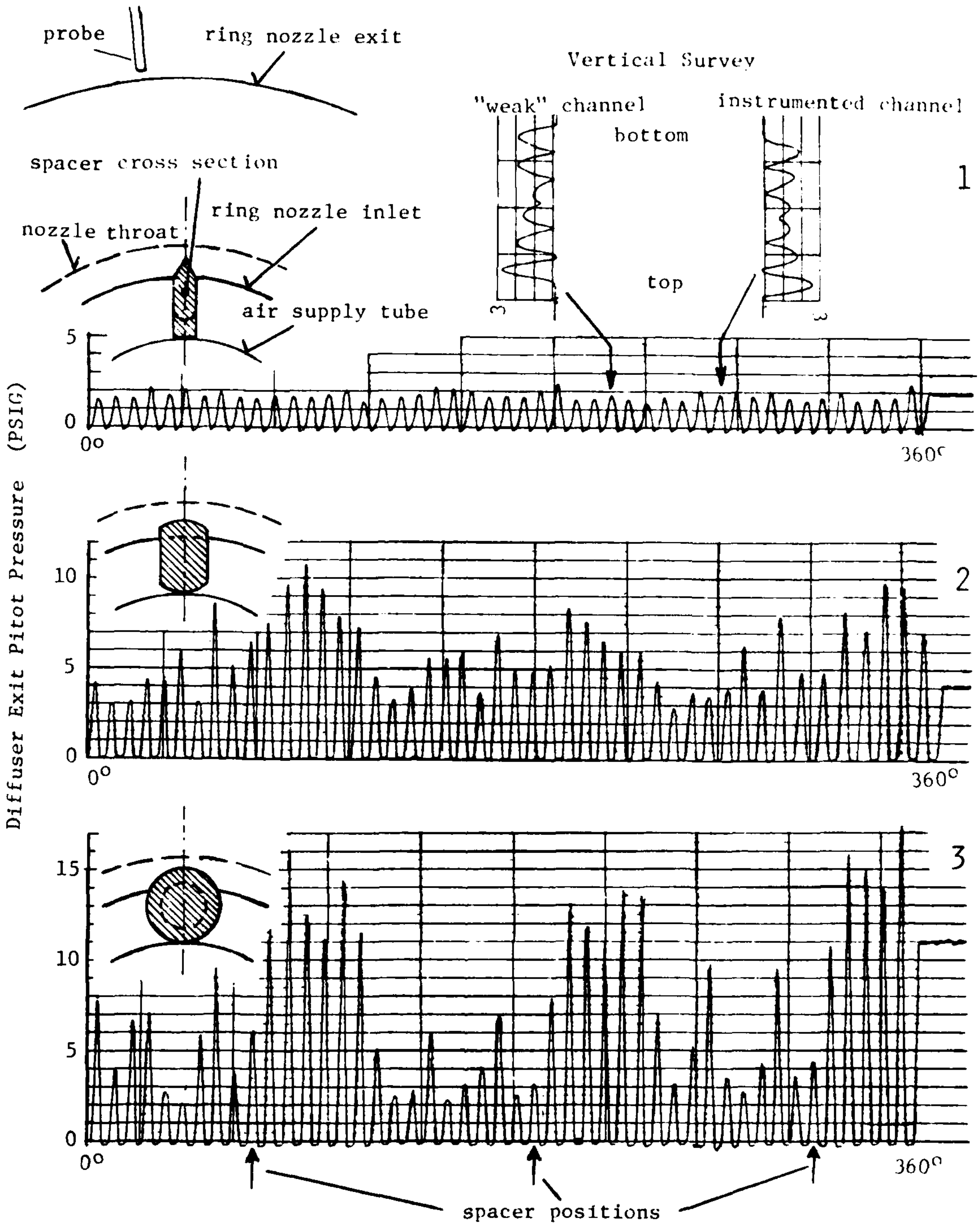

Figure 13. Peripheral Survey of the Diffuser Pitot Exit Pressure for Three Different Types of Ring Nozzle Spacers (Spacer on the top selected for diffuser investigations) Numbers on the right side of each survey identify the pertinent spacer in Figure 14)

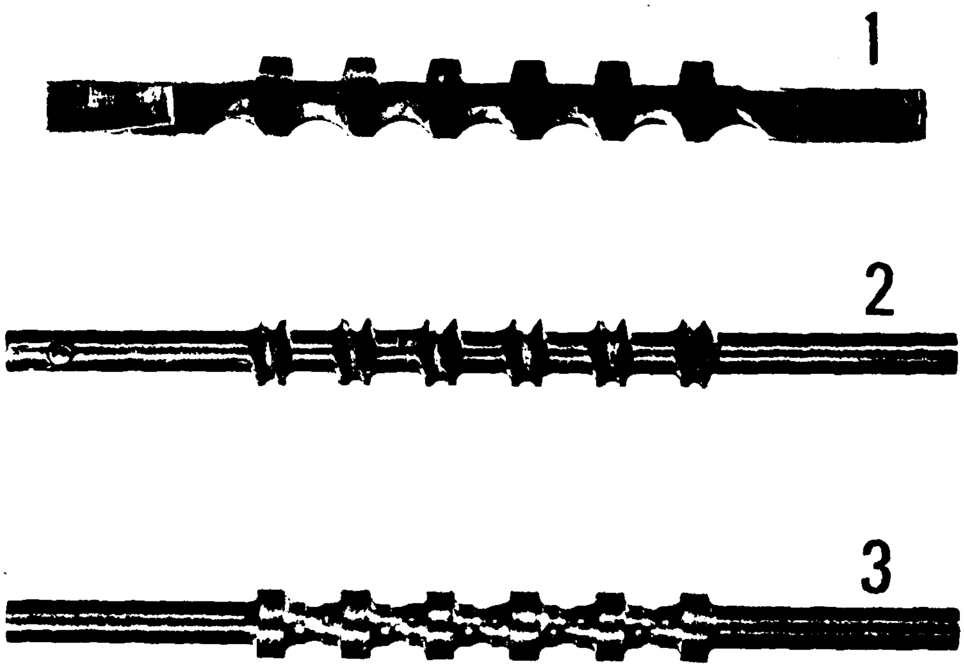

Figure 14. View of the Three Types of Nozzle Ring Spacers Investigated for Improving the Ring Nozzle System

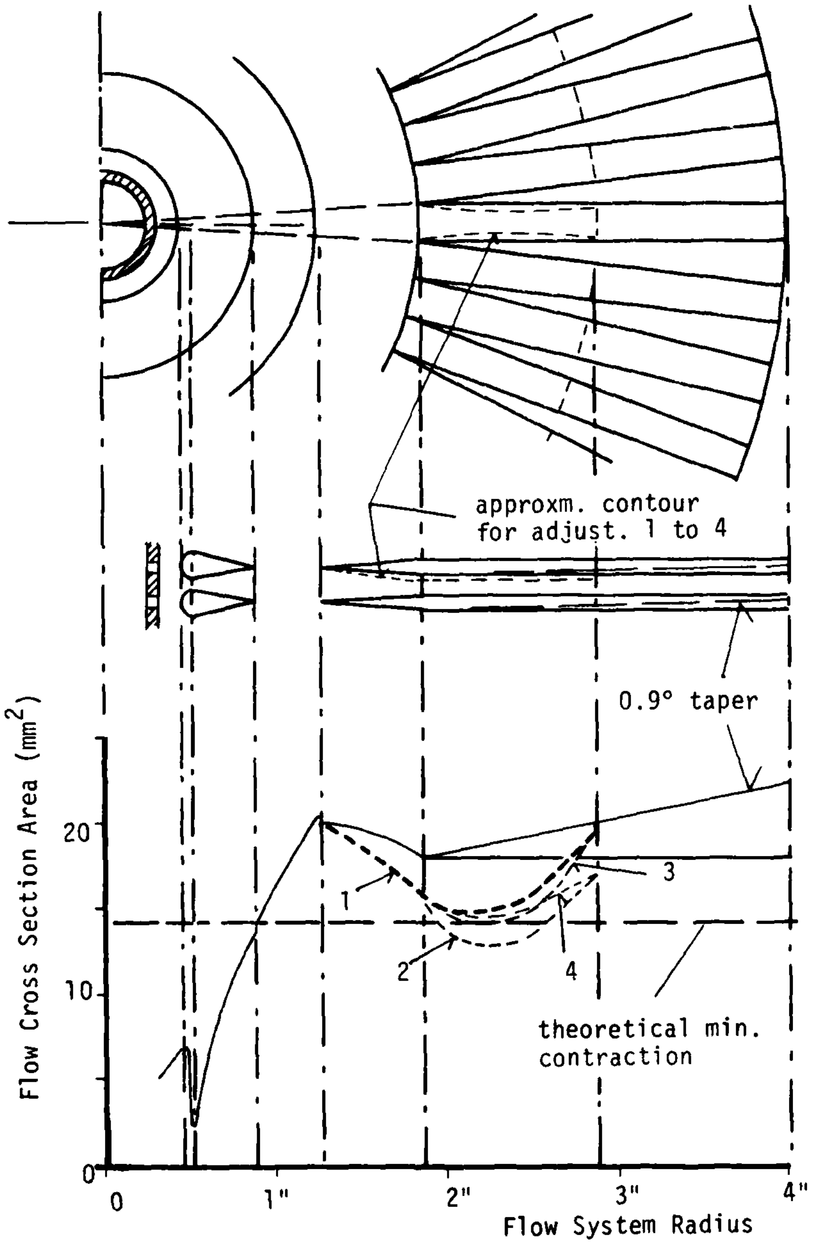

Figure 15. Flow Cross Section Area Schedules per Channel of the Radial Flow System with Wall Adjustments indicated (dashed lines). Adjustment (1) applied to complete diffuser; adjustments (2) to (4) applied to selected channels

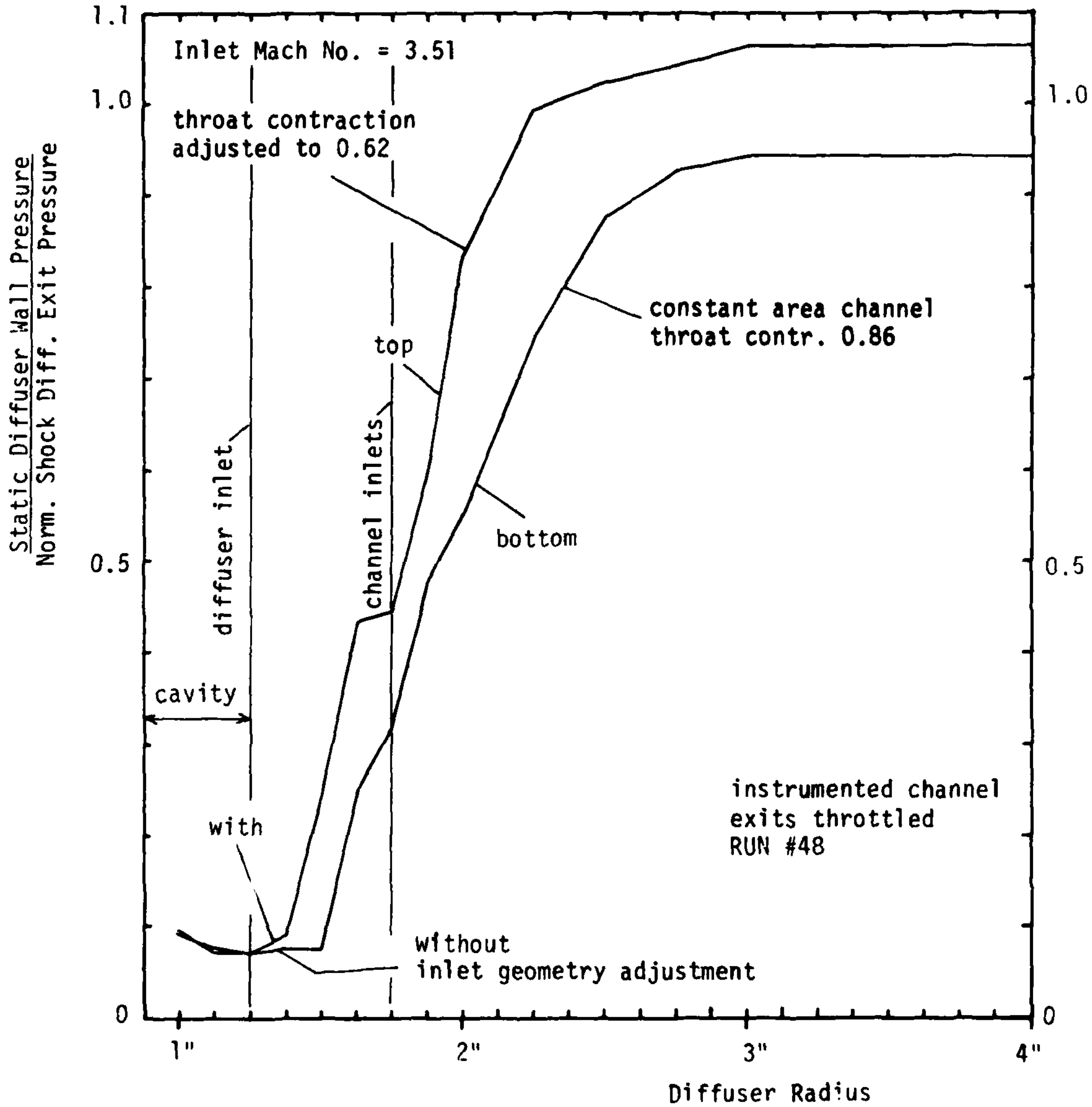

Figure 16. Comparison of the Single Channel Performances for Two Extreme Channel Geometries

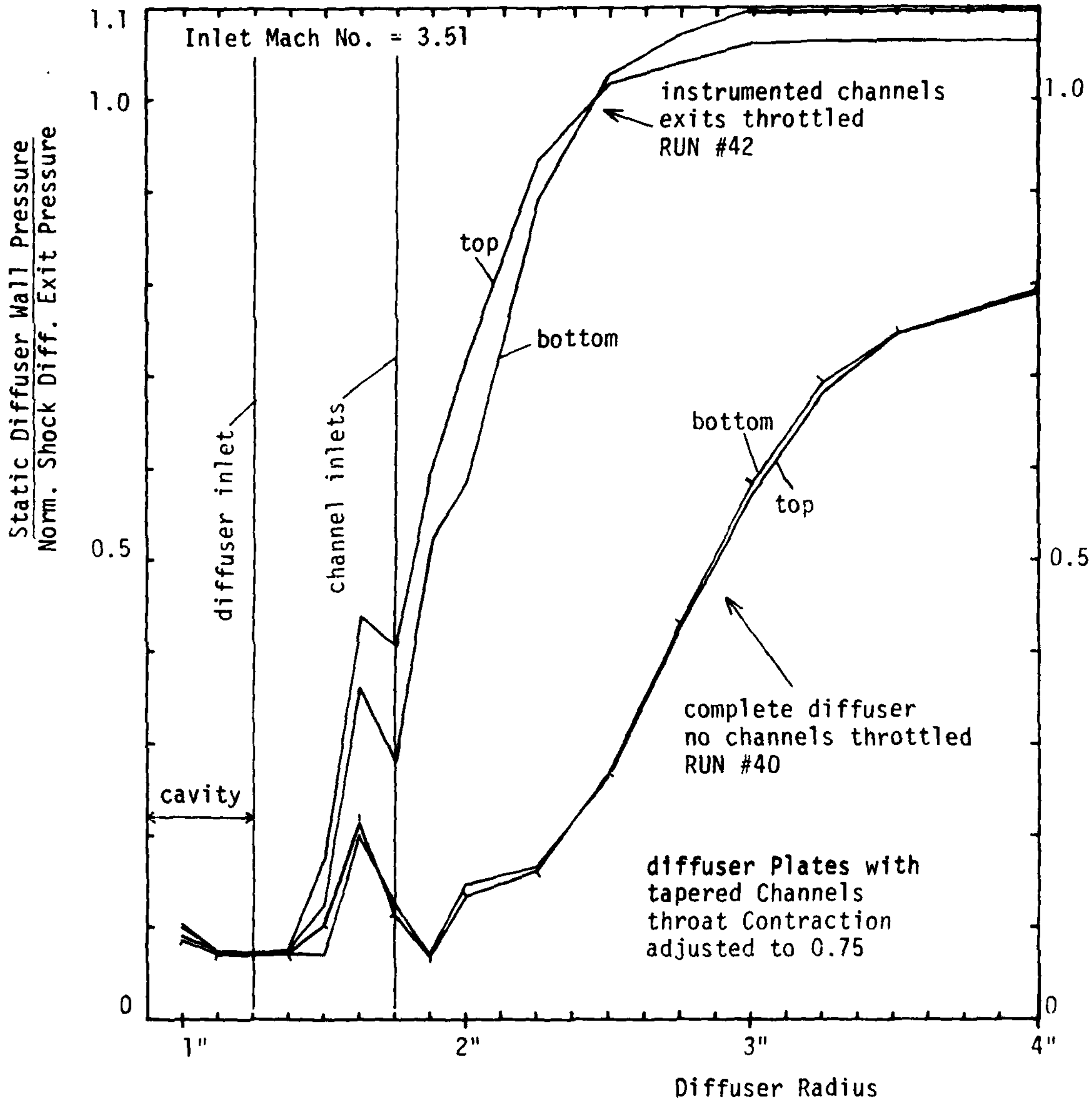

Figure 17. Typical Radial Diffuser Performance Compared with the Single Channel Performance for the same Channel Geometry

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